Applied Soft Computing 29 (2015) 436–449

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Tribilogical performances of connecting rod and by using orthogonal experiment, regression method and response surface methodology

He Zhenpeng[a], Sun Yigang[a,*], Zhang Guichang[a], Hong Zhenyu[a], Xie Weisong[b], Lu Xin[c], Zhang Junhong[c]

[a] Civil Aviation University of China, Tianjin, China
[b] School of Science, Tianjin University, China
[c] State Key Laboratory of Engine, Tianjin University, China

ARTICLE INFO

Article history:
Received 19 July 2013
Received in revised form
10 September 2014
Accepted 7 January 2015
Available online 14 January 2015

Keywords:
Connecting rod
Stepwise regression
Dynamic lubrication
Orthogonal experiment
Support vector machine (SVM)

ABSTRACT

Dynamic lubrication analysis of connecting rod is a very complex problem. Some factors have great effect on lubrication, such as clearance, oil viscosity, oil supplying hole, bearing elastic modulus, surface roughness, oil supplying pressure and engine speed and bearing width. In this paper, ten indexes are used as the input parameters to evaluate the bearing performances: minimum oil film thickness (MOFT), friction loss, the maximum oil film pressure (MOFP) and average of the oil leakages (OLK). Two orthogonal experiments are combined to identify the factors dominating the bearing behavior. The stepwise regression is used to establish the regression model without insignificant variables, and two most important variables are used as the input to carry out the surface response analysis for each model. At last, the support vector machine (SVM) is used to identify the asperity contact. Compared with SVM model, the particle swarm optimization-support vector machines (PSO–SVM) can predict the asperity contact more precise, especially to the samples near dividing line. In future work, more soft computing methods with statistical characteristic are used to the tribology analyses.

1. Introduction

It is estimated that mechanical friction loss accounts for around 10% of the total energy in the fuel for a diesel engine, and about 40–55% of the friction losses are due to the power cylinder system, made up of the piston (25–47%), ring-pack (28–45%) and connecting-rod bearings (18–33%) [1], so connecting rod also contributes main friction loss to the engine. A connecting rod assembly in an engine, which consists of rod, cap, bolts, big-end bearing and small-end bushing, the connecting rod serves as an important joint between the connecting rod big-end and crank pin. The connecting rod bearing is one of the most highly stresses tribological component in an engine because of the complicated dynamic loading and surface rubbing motion it encounters. The knowledge required for this particular task implies a good understanding of the connecting rod lubrication performances.

Bearings are the most important but also the most difficult elements to design, it is the most difficult to design due to the changeable bearing loads from the cylinder pressure and dynamic balance. From the literature reviewed, during the past two decades, many research articles had been written about the connecting rod bearing. Due to the important of flexible deformation and too many parameters which affect the lubrication, classic hydrodynamic lubrication model was development to elasto-hydrodynamic (EHD) lubrication or thermal elasto-hydrodynamic (TEHD) lubrication, nearly all the parameters that affect the performances were researcher. Fantino et al. [2,3] studied the effect of the deformation of an elastic automotive connecting rod on the oil film characteristics in the big-end bearing. Fantino and Frêne [4] studied the influence of the engine type petrol and diesel on the same result, but no conclusion could be made about the impact of other parameters load and speed, he also focused on the effect of the viscosity on the minimum film thickness for a connecting rod big-end bearing. However, as concerns the speed influence. Aitken [5,6] found an EHD parametric result, which shows a decrease of the minimum film thickness in the range 100–700 rpm. A more complete parametric study which involves the load, engine speed, and bearing stiffness on the lubrication is also reported. Okamoto et al. [7] reported the effects of bearing length and housing stiffness on the connecting rod big-end bearing. The results proved that the decrease of the bearing length has a significant incidence on the minimum film thickness and maximum pressure due to the load capacity reduction.

Because of too many parameters which affect the lubrication performances, it is hard to gain the comprehensive information, to overcome this difficult, many experimental runs need to carry out to evaluate the bearing performance. In order to reduce the number of experimental runs, the design of experiment method is researched recently. Francisco [8] used design of experiments to analyze the connecting rod big-end bearing behavior, and the main objective of the present work is to identify the factors dominating the bearing behavior. Smith [9] optimized the design of a piston-ring pack using design of experiment (DOE) methods. It is shown that an improved design can be achieved that reduces ring losses by 57% whilst reducing upward oil flow by 39%. Johansson [10] used the experiment to evaluate cylinder

* Corresponding author. Tel.: +86 02224092720; fax: +86 02224092720.
E-mail addresses: hezhenpeng@tju.edu.cn (Z. He), ygsun@cauc.edu.cn (Y. Sun), zhangguichang@tju.edu.cn (G. Zhang), zyhong@cauc.edu.cn (Z. Hong), weis_xie@tju.edu.cn (W. Xie), luzhougong@tju.edu.cn (X. Lu), zhangjh@tju.edu.cn (J. Zhang).

http://dx.doi.org/10.1016/j.asoc.2015.01.009
1568-4946/

Nomenclature

U_1	the velocity in the circumferential direction of the bearing ($U_1 = 0$)
U_2	the velocity in the circumferential direction of the crankshaft
h	the oil film thickness
p	the oil film pressure
η	the lubricant viscosity
x	the coordinate axis along the horizontal direction
y	the coordinate axis along the axial direction
φ_x	the pressure flow factors
φ_z	the pressure flow factors
φ_s	the shear flow factor
σ	the composite rms roughness
θ'	filling factor
c	represents the original radical clearance at the underformed state
ε_x	the crankshaft deformation in x direction
ε_z	the crankshaft deformation in the z direction
$\delta(\beta', z)$	radical deformation of the bearing
β'	measured from bearing crown
E'	the composite elastic modulus, $E' = ((1-\nu_1{}^2)/E_1 + (1-\nu_2{}^2)/E_2)^{-1}$
ν_i, E_i	the Poisson ratio and Young's modulus of the adjacent surfaces
η_s	the asperity density
β	the radius of curvature of convex peak
H	the dimensionless clearance parameter, $H = H/\sigma$
Q_1	flow-rate from the front-end plane of the bearing
Q_2	flow-rate from rear end of the bearing
Q	total end leakage flow rate of lubricant
τ_a	asperity contact shear force
τ_h	fluid shear force

liner/piston ring contact friction, it is shown that for the introduced DOE based tribometer test the interaction of dynamic viscosity, velocity and contact pressure can be studied within one experiment.

Apart from the researches about DOE, many researchers started to use the DOE to combine with intelligent algorithm to analyze the problem. Ko [11] applied artificial neural network and Taguchi method to preform design in metal forming considering workability. Papadopoulos [12] combined the experimental design with artificial neural networks to determine the chlorinated compounds in fish using matrix solid-phase dispersion, and the experimental results demonstrated that the proposed soft computing strategy is very effective and efficient to achieve satisfactory results. Benardos [13] Predicted the surface roughness in CNC face milling using neural networks and Taguchi's design of experiments, the data used for the training and checking of the networks' performance derived from experiments conducted on a CNC milling machine according to the principles of Taguchi DoE method. Hao [14] analyze the parameter sensitivity on deformation of composite soil-nailed wall using artificial neural networks and orthogonal experiment, 25 sets of tests are designed to analyze the sensitivity of factors affecting the maximum lateral displacement of composite soil-nailing wall. Chang [15] presents a systematic and cost-effective approach for process optimization with minimal experimental runs, all the optimization is based on neural network model and orthogonal arrays, and the proposed approach provides an effective and economical solution for process optimization.

From the literatures review, many researchers focused on the effect of parameters on lubrication, the dynamic lubrication characteristics or lubrication model. The purpose of this study is to numerically and roughly quantify the impact of each variable on the power loss, the flow rate, the MOFT and the MOFP. The knowledge required for this particular task implies a good understanding of the connecting rod. The orthogonal experiment is designed to do the research about the lubrication, parameters which response to the oil film thickness, the oil film pressure, the oil leakage and the friction loss are gained, the regression method is used to establish the prediction model which can bridge the gap between the recent numerical simulations and the need for a better understanding of the connecting rod bearing functioning. Considering the asperity contact can cause the friction loss to increase and the bearing to be failure earlier, the SVM technology is carried out to the asperity contact identification, which can help us to avoid asperity contact in the design.

2. Theory

2.1. Lubrication model

2.1.1. Governing equations

EHD lubrication analysis plays an important role in the design of dynamically loaded main bearings as it can offer more realistic prediction of the bearing performances. Apart from the bearing deformation, oil film cavitation is also very important to the bearing performance prediction. The earlier researchers Elrod and Adams [16], Vijayaraghavan and Keith [17] found cavitation phenomenon and established the cavitation model, then cavitation is researched widely. Boedo and Booker [18,19] investigated the effect of body force deformation and mass-conserving cavitation on the EHD behavior of connecting rod big-end bearings. Bonneau [20] and Optasanu [21] used a mass-conservative algorithm to simulate the EHD bearing behavior. The problem is solved analytically using Reynold's boundary conditions for film rupture. The governing equation concludes the full film region and cavitation region is rewritten as:

$$\frac{\partial}{\partial x}\left[\theta'\phi_x \frac{h^3}{12\eta}\frac{\partial p}{\partial x}\right] + \frac{\partial}{\partial z}\left[\theta'\phi_y \frac{h^3}{12\eta}\frac{\partial p}{\partial y}\right] = \left(\frac{U_1+U_2}{2}\right)\frac{\partial}{\partial x}\left(\theta' h + \theta'\sigma\phi_s\right) + \frac{\partial(\theta' h)}{\partial t} \quad (1)$$

where ϕ_x, ϕ_z is the pressure flow factors along x, z direction, ϕ_s is the shear flow factor, σ is the composite rms roughness, θ' is the filling factor.

2.1.2. Oil film thickness

The effect of elastic displacements of the bearing surface has to be included in EHD model. The film thickness including this effect is written as:

$$h(\beta, z) = c - \varepsilon_x(y)\cos\beta - \varepsilon_z(y)\sin\beta + \delta(\beta', z) \quad (2)$$

where c represents the original radical clearance at the underformed state, ε_x is the crankshaft deformation in x direction, ε_z is the crankshaft deformation in the z direction, $\delta(\beta', z)$ is the radical deformation of the bearing, β' is measured from bearing crown, $\beta' = \arctan(\varepsilon_z/\varepsilon_x)$ [22].

2.2. Lubrication characteristics evolution indexes

2.2.1. Oil leakage

The lubricant flow-rate Q_1 from the front-end plane of the bearing and the lubricant flow-rate Q_2 from rear end plane of the bearing are given by:

$$Q_1 = -\int_0^h \int_0^{2\pi R} \phi_x \frac{h^3}{12\eta}\cdot\left.\frac{\partial p}{\partial y}\right|_{y=0} dxdy \quad (3)$$

$$Q_2 = -\int_0^h \int_0^{2\pi R} \phi_y \frac{h^3}{12\eta}\cdot\left.\frac{\partial p}{\partial y}\right|_{y=L} dxdy \quad (4)$$

where Q_1 is the flow-rate from the front-end plane of the bearing, Q_2 is flow-rate from rear end of the bearing.

The total end leakage flow rate of lubricant is then calculated by:

$$Q = Q_1 + Q_2 \quad (5)$$

Q is the total end leakage flow rate of lubricant.